Magnetic Levitation through AC Excitation

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Abstract: **A combination of AC excitation and series tuned circuit can be used to levitate a ferromagnetic object by magnetic levitation technique. The electromagnet forms the inductive part of a resonating circuit. The circuit is tuned at a frequency less than that of the exciting frequency. Therefore when the distance between the object and the electromagnet increases, there is fall in inductance of the lifting magnet, the circuit approaches resonance and the coil current increases. The magnetic force on the object increases and the object moves to its desired position. Though the method is simple, for slow change in coil current the levitated object may move under influence of gravitational force and come to rest position. Hence a new circuit with Z-source inverter with shoot through is designed to bring the levitated object to its desired position.**

Key words: **Magnetic levitation, tuned circuit, Z source inverter.**

I. Introduction

Magnetic levitation is a technique used to maintain non contact surfaces. Because of the frictionless movement of the moving part it finds applications in the field of high speed maglev, bearingless motors, clean rooms etc. But the system is highly non linear, open loop and unstable. Recently lot of efforts has been taken towards the control of magnetic levitation system. Feedback linearization technique (1), fuzzy control (2) adaptive control (3), sliding mode control (4,5) have been widely used. The design of complicated controllers can be avoided by using tuned circuits for achieving suspension of objects. This method has been implemented by many authors (6, 7, 8, 9, 10).

In tuned circuit levitators, the electromagnet forms the inductive part of the tuned circuit and a capacitor is externally added. The LC series circuit is tuned at a frequency slightly less than that of excitation frequency. If the moving object moves away from the magnet, the fall in the inductance makes the circuit reach resonance. This increases the current through the magnet to increase the force exerted on the object and pulls it back to its desired position. Levitation is thus achieved without feedback control. This suspension cannot be maintained for long time as the object starts vibrating with low frequency oscillations (11).

To improve the performance of the tuned magnetic levitation system a new tuned circuit using Z-source inverter has been designed here to effectively bring the object to its equilibrium position. The commonly implemented tuned circuit works well for high L/R ratio. The lifting coil has inductance of 0.7 H and resistance of 5 ohms. So when the object deviates from its desired position the increase in the current due to circuit approaching resonance is strengthened by introducing a Z-source inverter. With the movement of the object the inductance of the coil varies and hence voltage across the tuning capacitor changes. This change is utilized to produce a shoot through to boost the voltage input of inverter to increase the current through the coil to produce sufficient force on the object to bring it to its equilibrium position.

II. The System

To achieve static stability a capacitor of 50 microfarads is added in series with the inductive magnet formed by the lifting winding (LC). For Y the distance between the levitated object and the LC, the inductance capacitance circuit is tuned for 'Y' equal to 0.011 meters. The excitation frequency is 50 Hz. Relation between inductance L_1 of the lifting coil LC and its distance Y from the object is given by

$$L_1(y) = a * \exp(-b * y) + c * \exp(-d * y) \qquad (1)$$

The force of attraction by the magnet is given by:

$$F_e = -\frac{1}{2} * (i(y))^2 * \frac{dL(y)}{dy} \qquad (2)$$

Where 'i' is the current through the LC winding and dL(y)/dy is differentiation of Equation (1) with respect to y. Though a power series has been widely used by several researchers (12, 13, 14) to represent relation between coil inductance and distance of the object from magnet but it was found that for the parameters considered, Equation (1) gave less residual error and also differentiation of Equation (1) resulted in simpler expression compared to the power series. Therefore Equation (1) has been used for this work. Values of various constants for Equation (1) are: a = 0.09085, b = 10.5, c = 2.369, d = 227.2.

Variation of force with respect to distance is shown in Figure 1. As the distance between the magnet and the object increase or decrease, this force varies. The object gains equilibrium position due to corresponding change in the current. The inductance of the magnet also changes and modifies the current and object is held in the desired position. As seen in Figure 1 at slightly less than 0.007 meters, the levitated object (LO) is at stable position as at this point the gravitational force and the magnetic force are equal.

III. Analysis of Oscillating Frequency

At equilibrium position the LO vibrates. The frequency of these oscillations (F_{os}) is theoretically found as

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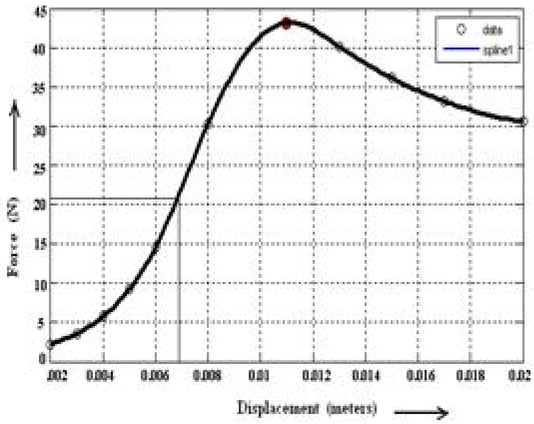

Figure 1 Force versus displacement

$$F_{os} = \sqrt{\frac{\text{Spring constant}}{\text{Mass of the object}}} = 4.8\text{H} \qquad (3)$$

$$\text{Spring constant} = \frac{dF_e}{dy} = 50227$$

The frequency of oscillations of the suspended object about the equilibrium position for the tuned LC (inductive capacitive) magnetic levitation system is also experimentally obtained as shown in Figure 2.

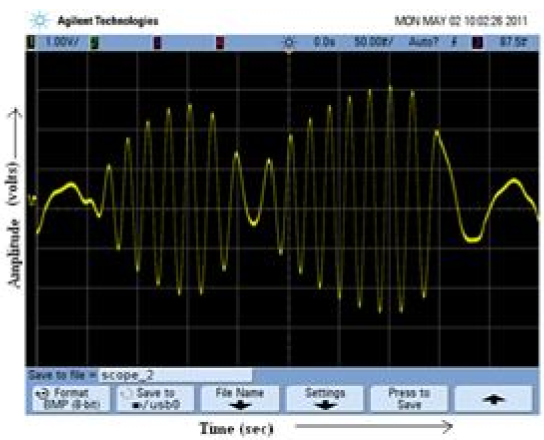

Figure 2 Waveform during vibrations

With simple tuned circuit when the object vibrated at its equilibrium position during experiment, these oscillations were recorded by DSO and are as in Figure 2. It is observed that 8 cycles of 50 Hz are there in half cycle of natural frequency as in Figure2. Therefore natural frequency of oscillations observed experimentally is 1/0.320= 3.125 Hz. As the magnitude of oscillations keep on increasing with time and there are other modes of oscillations also, measurement of frequency of oscillation with digital storage oscilloscope (DSO) is not very accurate but its order is however the same as that calculated theoretically. To minimize the oscillations of the LO and provide sufficient current (which is otherwise less due to low L/R ratio of the coil), to pull the object to its equilibrium position a new closed loop control method which uses the voltage change across the tuning capacitor and Z-source inverter with shoot through is designed.

IV. New Self Sensing Tuned System

The schematic of the system developed is shown in Figure 3. An impedance network couples the inverter main circuit to the power source of 10V. The resonance circuit which consists of the electromagnetic coil (which acts as the inductor) and a fixed tuning capacitor connected in series to the coil acts as the load for the Z-Source inverter. With the change in position of the object to be levitated the inductance value changes which in turn brings about a change in the voltage across the capacitor. This change in voltage is used to modify the inverter excitation by using PIC18f4550 microcontroller so as to produce required current to bring the object to its desired position. The working of the system is described in detail in the following section.

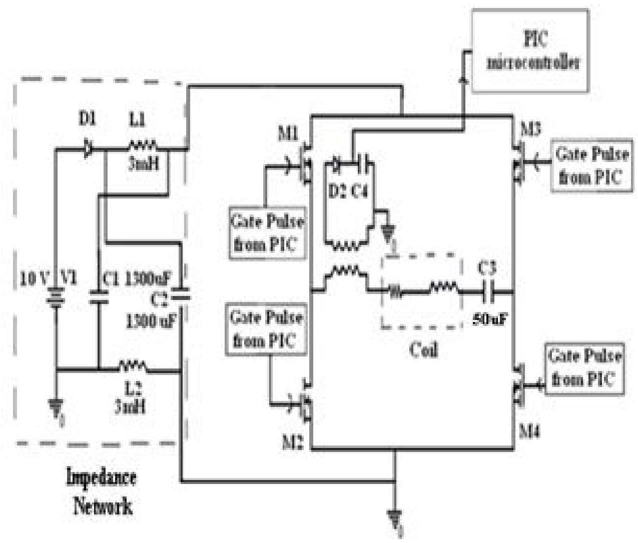

Figure 3 Schematic of the system developed

A. Z-Source Inverter

A Z-source inverter can perform both buck and boost operation depending on the parameter design and provide wide range of output voltage which is not feasible in conventional voltage source or current source inverters. The Z-source network has nine permissible switching states compared to the eight states of the conventional inverter. The extra switching state arises due to the shoot through state of the network in which two switching devices of the same leg can conduct simultaneously.

B. PWM Technique for Z-Source Inverter

There are three PWM techniques for pulse generation of a Z-source inverter viz; simple boost control, maximum boost control and constant boost control. Here simple boost control is used to reduce complexity of the circuit. In simple boost control when triangular carrier wave is greater than the upper envelope or lower than the bottom envelop, the circuit turns into shoot through state, else acts as traditional PWM. In this work only upper envelope is used.

C. Load for the Inverter Circuit

The electromagnet acts as an inductive (L) part with its internal resistance R and capacitor (C) of 50 uF connected

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externally to form the series LCR circuit. The circuit is tuned for the position of the levitated object at 0.011meters from the electromagnet. When the object is at its desired position, current flow through the inverter load is due to alternate conduction of MOS M_1, M_4 and M_3, M_2. For the gate pulse to the power switches of the inverter, a PIC18f4550 microcontroller is implemented. A simple boost control is implemented for the Z-source inverter. A sine wave is compared with a triangular wave to generate a PWM and shoot through period is generated when the triangular wave is greater than envelope. The envelope is the voltage across the tuning capacitor which varies with the inductance of the coil as the object deviates from its equilibrium position. With shoot through, excitation voltage for the inverter is increased. More current flows through the coil and pulls the object to the desired position. Figure 4 gives the SIMULINK model for generating gating pattern for MOSFET M1, M2, M3 and M4. During normal operation M1 and M4 of Figure 3 are triggered simultaneously and conduct and M2 and M3 conduct for the other half of the input cycle. When the input voltage for the inverter needs to be boosted, shoot through occurs as seen in Figure 5 and it is followed by the normal firing of the switches.

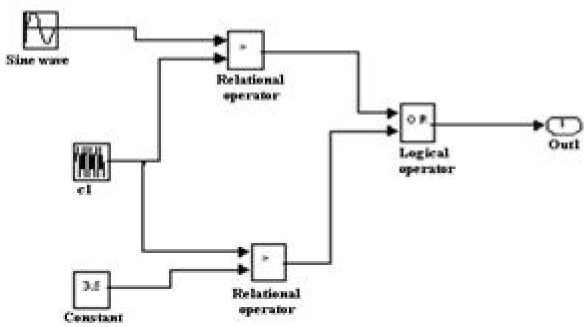

Figure 4 SIMULINK model for generating gating Pattern

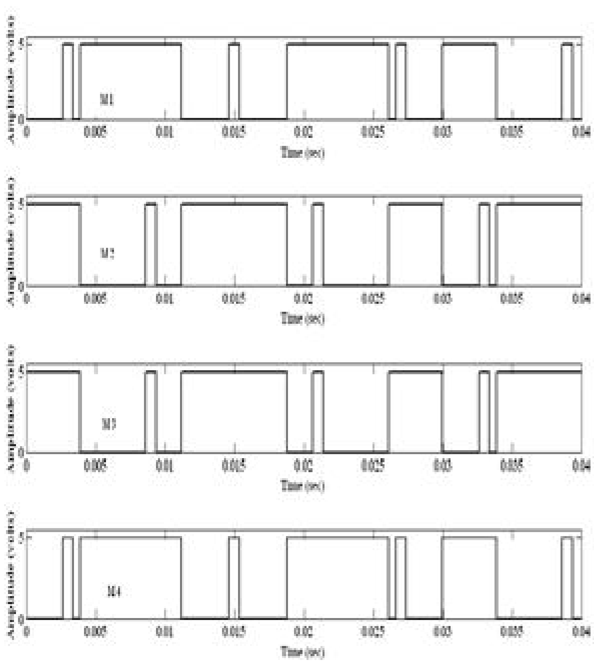

Figure 5 Gating pulses of inverter

V. Experimental Set Up

To develop the hardware, a symmetrical impedance network consisting of two identical capacitors and inductors connected in the manner as shown in Figure 3 is developed. The inverter circuit which follows the impedance network consists of four MOSFET switches. PWM pulses which are obtained from PIC18f4550 processor are given to the gate of the MOSFET's through optocoupler isolation circuit. This circuit offers electrical isolation between the power circuit and the PIC kit. The PIC microcontroller and the pulses generated using PIC during the experimental performance is as in Figure 6 and 7 respectively.

Figure 6 Pulses from PIC

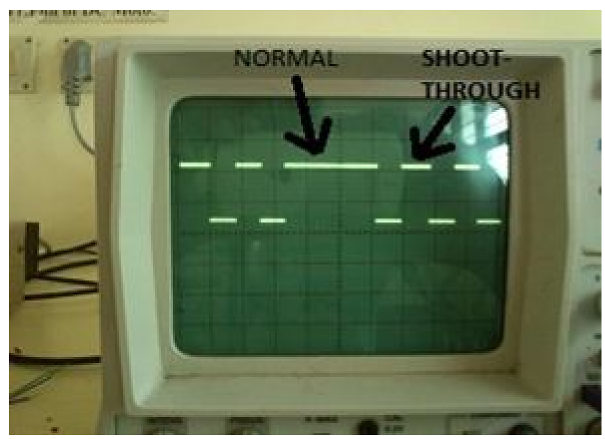

Figure 7 Change in pulse width with change in capacitor voltage

The pulse pattern in Figure 6 is under steady state. When the object deviates from its equilibrium position the change in voltage across the tuning capacitor result into generation of shoot through state as obtained in Figure 7. The excitation voltage of the inverter is boosted and current through the coil increases to pull back the object. The oscillations of the object obtained experimentally for the proposed new circuit are shown in Figure 8. It is observed that the oscillations are much reduced compared to that of the normal tuned circuit obtained in Figure 2. Hence it can be said that the designed new circuit also reduces the oscillations. The hardware modules are connected as in Figure 9.

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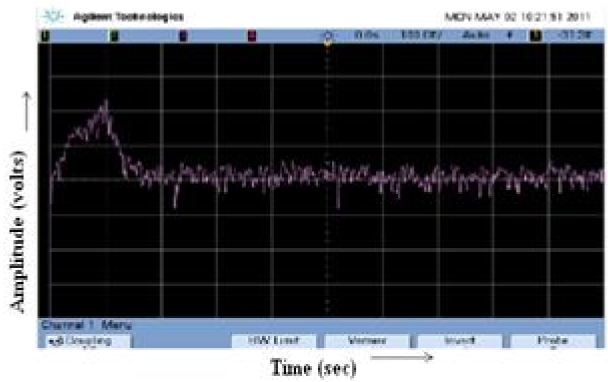

Figure 8 Oscillations of LO with Z-source inverter circuit

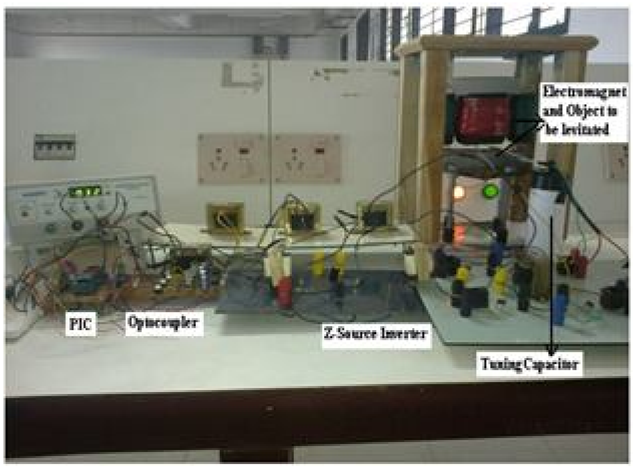

Figure 9 Experimental Set up

VI. Conclusion

Tuned inductive capacitive magnetic levitation circuit is designed and implemented. Experimental results show that the LO oscillates around its equilibrium position. The frequency of these oscillations obtained theoretically and experimentally does not show large variation. A new circuit with Z-source inverter is designed and implemented with the tuned circuit. It is observed that when the LO deviates from its equilibrium position, the circuit is no longer tuned and the voltage across the tuning capacitor varies. This voltage is used to generate shoot through condition to boost the excitation of the inverter. The resulting increase in the current produces sufficient force to pull the LO back to its desired position. Experimental results show that with this new circuit, the LO vibrates but with much reduced amplitude and hence can be said that the circuit also nearly damp out the oscillations. The main advantage of the system developed is it eliminates the sensors and its related drawbacks. Also design of complicated controllers is eliminated.

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